Plant-soil feedbacks as affecting ecosystem services in urban greenspaces

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ABSTRACT

Soils play a fundamental role in many ecological processes and in the provision of a multitude of vital ecosystem services not only in natural/semi-natural ecosystems but also in disturbed urban milieus. As many soil-derived ecosystem services are closely linked to human health and climate change, it is important to acknowledge the ability of urban soils to provide ecosystem services in the context of rapid urbanisation. Growing evidence shows that, despite various disturbances in urban landscapes, sparse vegetation can still control the provision of soil-derived ecosystem services in urban greenspaces due to the close linkages between aboveground and belowground milieus. Therefore, knowledge on the role of urban greenspace soils, in connection with plants, in providing ecosystem services likely leads to better urban planning and management practices.

The main objective of this thesis was to explore the mechanisms by which plants – plant functional types (evergreen trees, deciduous trees, lawns) in particular – affect soil carbon (C) and nitrogen (N) dynamics in urban parks of varying ages and in natural/semi-natural forests acting as a reference. Field experiments, including litter decomposition, root production, soil greenhouse gas emission, and soil inorganic N leaching, were conducted in boreal cities. Additionally, soils underneath impervious surfaces were investigated for the effects of soil sealing on soil C and N storage to better understand the role of urban soils (greenspace soils vs. sealed soils) in C and N accumulation under boreal climate.

I showed that evergreen trees (spruce, mostly *Picea* sp.) accumulate C and retain N in soils more than deciduous trees (linden, mostly *Tilia x vulgaris*) and lawn (grass/herb, mostly *Poa* and *Festuca* species). This was likely due to slow rates of litter decomposition and high root production of evergreen trees. Moreover, evergreen trees modified soil properties by lowering soil pH and soil moisture content efficiently, both of which can retard litter decomposition and N denitrification. Evergreen trees reduced soil greenhouse gas emissions and thus have a higher potential to mitigate the negative effects of anthropogenic N pollution and climate change in urban environments. Importantly, despite the various disturbances and management practices in urban parks, the mechanisms through which plant type controls soil C and N dynamics are independent of both habitat (urban parks vs. natural/semi-natural forests) and park age (young vs. old parks). Additionally, soil sealing has substantial, negative impacts on soil C and N storage, which critically hampers their ability to provide ecosystems services in cities under boreal climate.

I am the first to study the mechanisms behind plant-soil interactions as affecting ecosystem services in urban greenspaces in boreal cities. This thesis clearly highlights the importance of urban greenspace soils in providing ecosystem services under boreal climate and suggests that selecting the

right plant type, here evergreen trees, in urban greenspaces boosts the ability of urban soils in ecosystem services provision. As the build-up of organo-mineral associations strongly affects soil organic matter stabilisation, further research is needed to explore the potential effects of plant type on soil organo-mineral associations in urban greenspaces. Further research is also required to study how far away from trees plant-soil interaction extends in urban parks, which is important for determining optimal tree density in urban parks, and in accurately calculating C and N budgets at the park level.

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications, which are referred to in the text by their roman numerals:

I. **Lu, C.,** Kotze, D.J., Setälä, H.M., 2021. Evergreen trees stimulate carbon accumulation in urban soils via high root production and slow litter decomposition. Science of the Total Environment. 774, 145129. https://doi.org/10.1016/j.scitotenv.2021.145129

II. **Lu, C.,** Kotze, D.J., Setälä, H.M., 2021. Plant functional type affects nitrogen dynamics and can mitigate N-derived pollution in urban park soils. Manuscript.

III. **Lu, C.,** Kotze, D.J., Setälä, H.M., 2020. Soil sealing causes substantial losses in C and N storage in urban soils under cool climate. Science of the Total Environment. 725, 138369. https://doi.org/10.1016/j.scitotenv.2020.138369

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THE AUTHOR'S CONTRIBUTIONS

I Corresponding author. CL contributed to field samplings, carried out laboratory tasks and statistical analyses, designed and wrote the manuscript under the supervision of Heikki Setälä (HS) and Johan Kotze (JK).

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III Corresponding author. CL contributed to field samplings, carried out laboratory tasks and statistical analyses, designed and wrote the manuscript under the supervision of HS and JK.

ABBREVIATIONS USED IN THE THESIS

BD	bulk density
C	carbon
CH_4	methane
C/N ratio	carbon-to-nitrogen ratio
CO_2	carbon dioxide
LMM	linear mixed model
MANOVA	multivariate analysis of variance
N	nitrogen
NH_4^+	ammonium
NO_3^-	nitrate
N_2O	nitrous oxide
OM	organic matter

1. INTRODUCTION

1.1 Ecosystem services provided by urban greenspace soils

Ecosystem services are defined as the benefits provided by ecosystems to humans (MEA, 2005). Soil is fundamental to many ecological processes (Brady and Weil, 1999) and the provision of a number of vital ecosystem services (Wall et al., 2012). These ecosystem services include, for example, the provision of habitats for animals and plants, carbon (C) and nitrogen (N) sequestration, water infiltration and storage, detoxification of harmful substances, and climate regulation (e.g., Bolund and Hunhammar, 1999; Lal, 2004; Lehmann and Stahr, 2007; Valtanen et al., 2014). In terms of urbanisation, ca. 70% of world population are projected to live in urban areas by 2050 (United Nations, 2019). As many soil-derived ecosystem services are closely linked to human health (Wall et al., 2015; Li et al., 2018), the capacity of soils in urban areas to provide ecosystem services has increasingly gained attention (e.g., Pickett et al., 2001; Beier et al., 2008; Lorenz and Lal, 2009; Pouyat et al., 2010; Setälä et al., 2016).

Urban soils include both highly disturbed and relatively unaltered soils (Pouyat et al., 2010). Due to urbanisation, anthropogenic disturbances and environmental changes in urban areas impact urban soils and their functions, and likely soil-derived ecosystem services as well (Pouyat et al., 2002). Surprisingly, soils in urban greenspaces (including parks, residential lawns, remnant forests, etc.) have been shown to provide many of the same supporting, regulating, and provisioning ecosystem services as natural/unaltered soils (Effland and Pouyat, 1997; Pouyat et al., 2010; Pouyat et al., 2020; O'Riordan et al., 2021). For example, urban greenspace soils can store comparable amounts of C or even more than native soils (Frank et al., 2006; Pouyat et al., 2009; Raciti et al., 2011; Edmondson et al., 2014; Vasenev and Kuzyakov, 2018). Furthermore, urban greenspace soils can retain nutrients and heavy metals and thus mitigate the adverse effects of traffic and industrial pollution, also on water quality (Valtanen et al., 2014; Yang et al., 2015; Nidzgorski and Hobbie, 2016; Setälä et al., 2017).

Carbon, as the “common currency” in ecosystems (Reekie and Bazzaz, 1987), strongly controls soil functions and ecosystem services (Franzluebbers, 2002). Given that urban areas are the major source of greenhouse gas emissions that result in global climate change (Grimm et al., 2008), the ability of urban soils, especially those in greenspaces, to store C – as well as N – is considered one of the most important ecosystem services in urban areas (Pataki et al., 2006; Pouyat et al., 2010). In Finland, for example, ca. 80% of total C in urban parks is stored in soils, i.e., brown infrastructure, and the rest in trees i.e., green infrastructure (Lindén et al., 2020). This clearly emphasises the importance of urban greenspace soils in storing C in boreal climate (Setälä et al., 2016). As above- and belowground are closely interlinked (Wardle, 2002; Wardle et al., 2004), a better understanding of the effects of vegetation on urban soils is needed to improve the capacity of urban soils to provide ecosystem services.

1.2 Plant functional type effects on ecosystem services of urban greenspace soils

Plants with divergent traits, such as growth rate, litter quality and nutrient uptake strategy, have different ecological strategies and thus can be classified into different functional types (Cornelissen et al., 2003). Studies have shown that plant functional type can modulate soil formation and processes not only in natural ecosystems (e.g., Ponge, 1993; Finzi et al., 1998; Pickett et al., 2001; Wardle, 2002; Hobbie, 2015), but also in managed urban greenspaces (e.g., Vauramo and Setälä, 2010; Edmondson et al., 2014; Bae and Ryu, 2015; Livesley et al., 2016). In natural ecosystems, slow-growing conifers (hereafter referred to as evergreen trees) that produce low quality and recalcitrant litter tend to acidify topsoil and are associated with drier soil conditions, lower water discharge and soil nutrient availability compared to deciduous broadleaf trees (hereafter referred to as deciduous trees) (Wardle et al., 2004; Smolander and Kitunen, 2011; Augusto et al., 2015; Rożek et al., 2020). Similarly, the ability of urban greenspace soils to provide ecosystem services is strongly influenced by vegetation (Setälä et al., 2016, 2017; Kotze et al., 2021). Recent evidence suggests that, in urban parks, evergreen trees tend to have a higher ability to provide ecosystem services compared to deciduous trees (Setälä et al., 2016, 2017). For example, evergreen trees are associated with higher soil organic matter (OM), C and N storage than deciduous trees and lawns in boreal cities (Setälä et al., 2016). However, little is known about the mechanisms through which plant functional type affects soil C and N accumulation in these strongly disturbed urban greenspaces.

In natural ecosystems, differences in the ability among plant types to store C and N depend on inputs and outputs of C and N (Knops et al., 2002; Vesterdal et al., 2013), i.e., through differences in the quality and quantity of litter that plants return to the soil (Bardgett and Wardle, 2010). For example, recalcitrant litters (e.g., litter with a high C/N ratio and/or with a high content of polyphenols) decompose slower than labile litters (low C/N ratio) and thus enhance soil C and N accumulation (Wardle et al., 2004). In urban ecosystems, however, various anthropogenic disturbances and management practices that can affect C and N inputs likely give rise to different soil C and N dynamics compared to natural ecosystems (Kaye et al., 2006; Lorenz and Lal, 2009). Moreover, information on the contribution of plant root production – the major source of C in natural forests (Vesterdal et al., 2008) – to soil OM accumulation in urban systems is lacking. Therefore, it is unclear to which degree the effect of plant type on OM and C accumulation in urban greenspaces relates to litter decomposition and root production.

In terms of N, studies have shown that plant type can affect soil total N content in urban greenspaces (Setälä et al., 2016; Kotze et al., 2021). However, it is still unclear whether plant type influences soil N dynamics. Plant can modify soil physico-chemical properties and its biota (e.g., Edmondson et al., 2014; Setälä et al., 2016; Francini et al., 2018) and thus affect N mineralisation, nitrification and denitrification (Haimi et al., 1992; Ste-Marie and Paré, 1999; Lavelle et al., 2004). The high accumulation of soil N under evergreen trees may reflect a high ability of these soils to reduce NO_3^- leaching and N_2O emissions. However, urban soils are typically saturated with N due to high N deposition (Lovett et al., 2000; Fang et al., 2011). Yet, little is known about whether the excess anthropogenic N input in urban environments will weaken the effects of plant type on soil N dynamics in urban greenspaces. Given the negative effect of NO_3^- leaching on water quality and of N_2O emissions on climate change, knowledge about plant type effect on N dynamics of urban soils is needed.

In natural ecosystems, the magnitude of the plant effect on soil characteristics increases with the time that plant-soil interactions have occurred (De Deyn et al., 2008). Similarly, in urban greenspaces, the plant type effect on soils has been reported to accentuate with park age, i.e., time since park construction (Raciti et al., 2011; Livesley et al., 2016; Setälä et al., 2016). In boreal climate, for example, soil C and N storage in urban parks clearly increases with park age (Setälä et al., 2016; Lindén et al., 2020). Furthermore, the difference in soil C and N concentrations, and soil microbial biomass among plant types is much clearer in old than in young parks (Setälä et al., 2016; Francini et al., 2018). However, virtually nothing is known about whether park age affects the mechanisms by which plant types influence soil C and N dynamics in urban greenspaces.

1.3 Impacts of soil sealing on C and N storage of urban soils

Urbanisation is drastically and rapidly changing urban land cover to meet human demands (Grimm et al., 2008), and soil sealing is one of the most prominent land use changes (Pataki et al., 2006; Pouyat et al., 2006). More than 600 000 km^2 of urban areas around the world have been sealed with impervious surfaces, e.g., roads, buildings and other grey infrastructure (Liu et al., 2014). Soil sealing can result in many negative effects on soil ecological processes (Scalenghe and Marsan, 2009). For example, water and gas movement, organic matter input, and microbial activity are inhibited in sealed soils (Kaye et al., 2006; Lorenz and Lal, 2009) causing a serious threat to urban soils (van der Putten et al., 2018). A better understanding on the impact of soil sealing on C and N storage is required to accurately estimate C and N budgets in urban areas where impervious surfaces are the dominant cover types (Liu et al., 2014).

Unlike urban greenspace soils, most research has overlooked the ability of sealed soil to provide ecosystem services. Thus far, only few studies conducted in temperate and subtropical cities have investigated the effect of soil sealing on soil C and N content, and microbial activity. These studies have shown that soil sealing significantly reduce C and N storage (e.g., Raciti et al., 2012; Wei et al., 2014; Yan et al., 2015; Majidzadeh et al., 2017), microbial biomass and activity (Zhao et al., 2012; Wei et al., 2013; Majidzadeh et al., 2018), and also change the composition of the soil microbial community (Hu et al., 2018; Hu et al., 2021; Pereira et al., 2021). These negative effects likely result from i) the replacement of top natural soils rich in C and nutrients by constructing materials with very little C and N, and/or ii) the lack of plant-soil interactions disconnected by impervious surfaces (Majidzadeh et al., 2017; Majidzadeh et al., 2018).

Although urban areas account for less than 5% of the global terrestrial surface (Schneider et al., 2010), urban areas can strongly alter global biogeochemical cycles (Grimm et al., 2000). However, as data on C and N content underneath impervious surfaces are scarce, especially so in boreal climate where most of C is stored in soils (Liski and Westman, 1997), C and N budgets of urban soils are likely substantially under- or over-estimated. For example, in Finland, top natural soils rich in C and nutrients are removed and replaced by a construction layer (ca. 1 m deep, mostly gravel and crushed rock) before sealing in order to prevent up-lifting of asphalt/houses due to freeze-thaw effects during the cold season. As a result, soil sealing can be expected to cause much more C and N losses in boreal cities than in warmer cities. Given the importance of soil C and N accumulation in mitigating climate change (Loren and Lal, 2009), a better understanding of soil sealing effects on soil C and N storage is needed to improve the sustainability of cities (Lorenz and Lal, 2015).

2. AIMS OF THE THESIS

It is well known that plants influence a variety of soil processes, but the degree to which different plant types modify these processes, especially in urban environments is less clear. In particular, the mechanistic understanding behind the factors that control plant-soil interactions in urban greenspaces is non-existing. The main aim of this thesis was to increase our knowledge on the role of urban greenspace soils, in connection with plant functional types, in providing ecosystem services (C and N accumulation). Field experiments, including litter decomposition, root production, soil greenhouse gas emission, and soil inorganic N leaching, were conducted in urban parks of varying ages and in natural/semi-natural forests as controls in two cities (Helsinki and Lahti) in Finland to investigate the following research questions:

1) What are the mechanisms that cause the divergent C and N accumulation patterns underneath three plant functional types (evergreen trees, deciduous trees, and lawns) (I, II)?
2) Does park age influence the mechanisms by which plant type affects soil C and N dynamics (I, II)?
3) Do the various human-induced disturbances in urban greenspaces influence the ability of plant type to modify soils, i.e. does the plant type effect on soil C and N dynamics differ between urban parks and natural/semi-natural forests (I, II)?

Additionally, nothing is known about soil sealing effects on the ability of urban soils to provide ecosystem services under cold climate. This knowledge is required because the massive soil removal during infrastructure construction is expected to cause substantial C and N losses in boreal cities. Therefore, soil samples underneath impervious surfaces in the city centre of Lahti were taken to investigate

4) how much soil C and N is stored underneath impervious surfaces in a boreal city (III).

The aim of the first two papers was to explore whether the disturbances in urban parks are strong enough to distort natural C and N dynamics by comparing plant type effects on soil C (I) and N (II) dynamics between urban parks and native forests. The aim of the third paper (III) was to evaluate the impact of soil sealing on C and N storage of urban soils under boreal climate.

The main hypotheses were:

1) Soil C and N accumulation relates to both litter decomposability and root production (I, II).
2) Plant type affects soil C and N accumulation through the same mechanisms in young and old parks, but plant type effects are magnified in old parks (I, II).

3) Plant type effects on soil C and N dynamics are less pronounced in managed urban parks than in natural/semi-natural forests (I, II).
4) In boreal climate, soil underneath impervious surfaces plays a smaller role in C and N accumulation compared to urban greenspace soils (III).

3. MATERIALS AND METHODS

3.1 Study sites

The three studies in this thesis were conducted in two cities in southern Finland: Helsinki (60°10′15″ N, 24°56′15″ E) and Lahti (60°59′00″ N, 25°39′20″ E). The population size is ca. 1.3 million in Helsinki and ca. 120 000 in Lahti. The annual temperature and mean precipitation are 5.8 °C and 656 mm in Helsinki, and 4.4 °C and 653 mm in Lahti (Finnish Meteorological Institute).

To study plant functional type effects on soil C and N dynamics in urban greenspaces (I, II), a total of 27 urban parks (13 in Helsinki and 14 in Lahti) were selected and classified into two age groups: young parks (5-15 years old) and old parks (> 70 years old). These selected parks (0.1 to several hectares in size, mean = 0.5 ha) were neither irrigated nor fertilized but were frequently mowed and raked after park establishment (for information on park construction, see Setälä et al., 2016). Mowing residues remained on the lawns and tree leaf litters were removed in the fall and spring. Three plant functional types: evergreen tree (spruce, mostly *Picea* sp.), deciduous tree (linden, mostly *Tilia x vulgaris*), and lawn (grass/herb, mostly *Poa* and *Festuca* species) were included in the study design (Fig. 1). The three distinct plant types were selected as they differ in plant functional traits, and are typical to the study area. To ensure five replicates per plant functional type per park age per city, at least one of the three plant types was selected in each studied park. Park age refers approximately to tree age. As lawn cover extended under the canopy of trees, the study design is essentially lawn without trees, and an individual tree (either evergreen or deciduous) with lawn. Study plots (2 m^2 in size) were located in the middle of the lawn and right underneath the canopy projection of the two tree types. In terms of lawn plots, to minimise tree effects on lawn soils, the distance of the lawn plots to the nearest trees was always greater than the height of the tree. Underneath the two tree types, the distance between study plots and the trunk of the selected trees varied from one to several meters, depending on the size of tree canopy.

In addition to urban parks, 10 undisturbed natural/semi-natural forests (> 80 years old) were selected as references sites to compare differences in plant type effects on soils between urban and natural habitats. All selected reference forests were located in nature conservation areas adjacent to the city of Helsinki or Lahti (5 forests in each city). Both evergreen (Norway spruce, *P. abies*) and deciduous trees (forest linden, *T. cordata*) were present in each reference forest. Furthermore, both tree types formed almost monocultural type stands (0.01-0.5 ha in size). Lawn was lacking in all reference forests. Therefore, in reference forests, lawn was not included in the study design (Fig. 1), resulting in a total of 80 study plots: 60 plots in urban parks (3 plant functional types × 2 park ages × 5 replicates × 2 cities) and 20 plots in reference forests (2 plant functional types × 5 replicates × 2 cities).

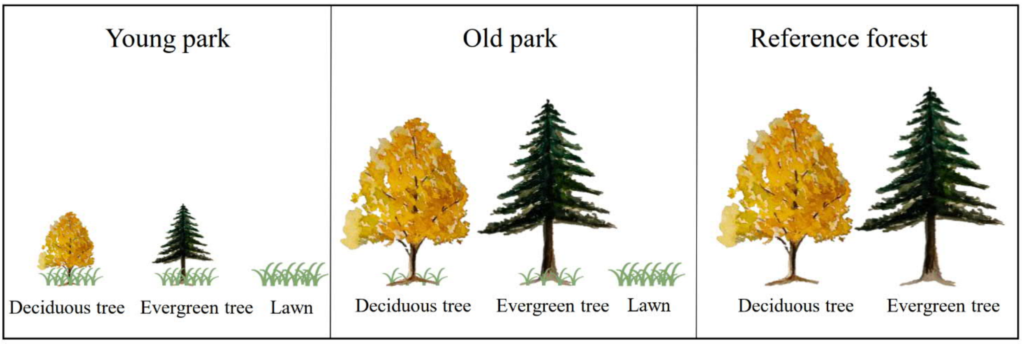

Figure 1. Study design with three habitats: young park, old park and reference forest.

To study soil sealing effects on soil C and N storage under cool climate (III), 13 sites distributed across the city centre of Lahti were selected (Fig. 2A). These 13 sites include 6 roadside pavements, 6 main streets and 1 block of flats, where impervious surfaces were temporarily removed for construction work and soil pits were exposed. At the selected sites, the depth of the construction layer varied from 60 to 120 cm (average depth = 96 cm).

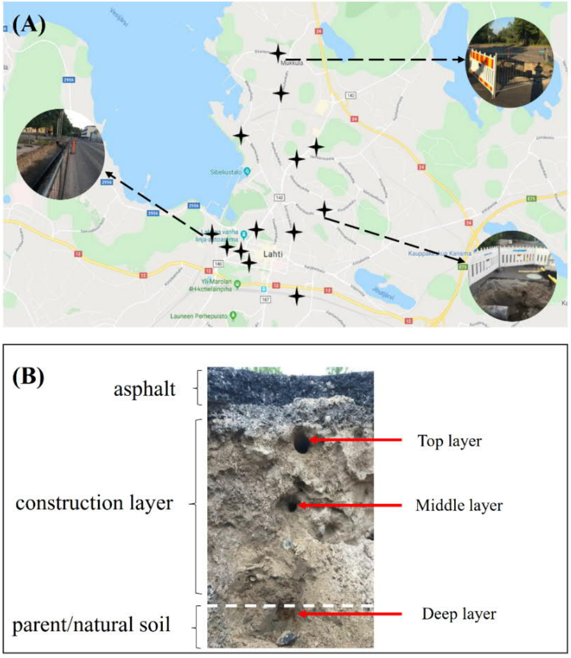

Figure 2. Locations of the 13 sampling sites (A), and an example of a soil profile (B) in the city of Lahti, Finland.

3.2 Field sampling and experiments

Soil sampling

At each study plot in the urban parks and reference forests (I, II), three soil subsamples (depth 0-10 cm) were taken using a metal soil corer (diameter = 2.54 cm) and then pooled. A total of 80 soil samples were collected from May to June 2020. Soils underneath impervious surfaces (III) were sampled at 13 sites in Lahti from three layers (Fig. 2B): top layer (0-10 cm below the asphalt), middle layer (45-55 cm below the asphalt), and deep layer (the native soil below the construction layer) from June to August 2018. From each layer, 500 cm^3 of soil was collected. As the deepest layer sample underneath a house could not be collected, a total of 38 samples were taken from 13 sites. Additionally, data of pervious park soils modified from Setälä et al. (2016) were used in study III for comparative purpose. The data of pervious soils were collected by Setälä et al. (2016) from underneath old park lawns at three layers: top layer (0-10 cm), middle layer (11-20 cm), deep layer (21-50 cm).

Earthworm sampling

In October 2020, earthworms (II) in the 40 study plots in Helsinki were collected using the hot mustard liquid method (Gunn, 1992). The collected earthworms were first stored in the laboratory for 48 h and then identified and weighed.

Litter decomposition

To explore the relationship between litter decomposition and soil OM accumulation (I), a reciprocal litterbag experiment was conducted in the 60 urban parks plots in Helsinki and Lahti, and in the 10 reference forest plots in Lahti. Two litter types (spruce needle litter and linden leaf litter) were used in this experiment. In November 2016, twelve litterbags (six of each litter type) were buried in the soil to a depth of 2 cm per plot, resulting in a total of 840 litterbags. In November 2017 and November 2018, six litterbags (three of each litter type) were retrieved from each plot, respectively. The remaining litter in the litterbags was cleaned from debris, oven-dried and weighed in the laboratory.

Root production

The root ingrowth method was used to study the contribution of root production to soil OM accumulation (I). In mid-November 2018, two cylindrical root ingrowth cores with root-free soil were placed into holes (0-15 cm) in the soil at each plot in Helsinki, including 30 urban park plots and 10 reference forest plots. All the root ingrowth cores (80 samples) were retrieved in mid-November 2019. The collected roots were washed, sorted to plant type, oven-dried and weighed in the laboratory.

Soil inorganic N content

The effects of plant functional type on soil inorganic N dynamics were investigated by using ion exchange resin bags (II). This experiment was conducted in the 40 plots in Helsinki. In each plot, two resin bags were buried in the soil (10 cm deep). One of the two resin bags was buried in mid-November 2018 and retrieved in mid-May 2019; another one was buried in mid-July 2020 and retrieved in mid-November 2020. The retrieved resin bags were delivered back to the supplier (UNIBEST International, WA, USA) for the analysis of NH_4^+ and NO_3^- content adsorbed by the resin in the bags.

Greenhouse gas fluxes

The static chamber method (Kanerva et al., 2007) was used to quantify soil greenhouse gas (CO_2, CH_4, N_2O) fluxes beneath the three plant types (I, II). Gas samplings were conducted in the 40 study plots in Helsinki in late June 2019 (summer), mid-October 2019 (fall), and early May 2020 (spring). Two chambers were placed at each plot and gas samples were taken at two time points: 0 and 30 min thereafter. A total of 480 gas samples were taken during the three sampling seasons and were analysed in the laboratory using a gas chromatograph.

3.3 Physico-chemical and biological analyses

Before analysing soil physico-chemical properties, soil samples were sieved through a 2 mm sieve. Soil pH was measured in 1/5 (v/v) fresh soil/distilled water suspension. Percentage soil moisture was determined by drying the soils at 105 °C for 24 h. Soil OM (%) was determined by loss on ignition (at 550 °C in a muffle furnace for 5 h). Soil total C and N were analysed by dry combustion at 1350 °C using a LECO CNS-2000 Elemental Analyser. Soil bulk density (BD) was calculated based on dry mass and volume of non-sieved soil. Soil microbial activity was determined by measuring CO_2 production (an indicator of soil microbial activity) of non-sieved, melted soils under laboratory condition using an Apollo 9000Hs TOC analyser.

3.4 Statistical analyses

All statistical analyses were performed in R 3.6.1 (R Core Team, 2019). Histograms and Shapiro-Wilks test were used to determine normality of the response variables, which were square-root or Ln transformed, when necessary. In both study I and II, two comparisons were performed using linear mixed models (LMM) to test plant type effects on the response variables, including measured soil properties, litter mass loss, root production, earthworm biomass, greenhouse gas fluxes (CO_2, CH_4 and N_2O), and inorganic N content in the resin bags (NH_4^+ and NO_3^-). The first comparison is to compare the three plant types in parks of different ages (young vs. old parks), and the second is to compare the two tree types between old parks and reference forests of similar ages (old parks vs. reference forests). The LMM for the first comparison included two factors: plant type and park age, and their interaction. Here, plant type has three levels: evergreen tree, deciduous tree, and lawn; park age has two levels: young and old. Likewise, the LMM for the second comparison also included two factors: plant type and habitat, and their interaction. However, unlike the first one, here plant type has only two levels: evergreen tree and deciduous tree. This is because lawn was not included in the study design of the reference forests. Habitat has two levels: old parks and reference forests. When testing the plant type effects on the rate of litter decomposition (I), litter type was also included in the model as a factor with two levels (spruce needle and linden leaf). In all the LMMs, site identity was included as a random effect either with or without being nested within city, depending on the study design. To select the best model, insignificant interactions ($p > 0.05$) were removed, but main effects were always kept in the models irrespective of their significance.

In study III, a multivariate analysis of variance (MANOVA) was used to test the effect of soil depth on soil variables, including pH, %C, %N, %OM, C/N ratio, moisture content, bulk density, and soil respiration. As the depth of the three soil layers differed between impervious and pervious soils, data of the two soil types were analysed separately but plotted in the same graph for comparative purpose.

4. RESULTS AND DISCUSSION

4.1 Effects of plant functional type on soil C and N accumulation in urban greenspaces

Plant functional type had clear effects on soil C and N accumulation in urban parks (I, II). As expected, evergreen trees were associated with clearly higher soil total OM and C and slightly higher N concentrations in comparison to those under deciduous trees and lawns, but only in old parks (Fig. 3A, C & E). The high soil OM and C concentrations under evergreen trees are expected to relate to the slow decomposition of needle litter (I), which can also, at least partly, explain the high N under evergreen trees given the close link between C and N in biogeochemical cycles (Vitousek et al., 1997) (II). Spruce litter (C/N ratio = 38.1) decomposed at a significantly slower rate than linden litter (C/N ratio = 29.4), independent of park age and host plant type (Fig. 4). This is in line with previous findings reported in forest ecosystems that litter type/quality affects the rate of litter decomposition (Prescott et al., 2000; Strickland et al., 2009) and soil OM accumulation (Swift et al., 1979). It is worth noting that the spruce litter used in this thesis was partly decomposed before starting the litter decomposition study, and thus may not be as recalcitrant as recently senesced litter (C/N ratio = 72, Smolander et al., 1996). Moreover, the influence of earthworms on litter decomposition was excluded due to the small mesh size of litterbags. Therefore, the difference in mass loss between spruce and linden litter in the 'real world' would be even bigger than detected in this thesis.

Besides the intrinsic differences in litter decomposability, plant type can also affect C and N accumulation indirectly by modifying soil physico-chemical properties and soil earthworm abundance. For example, soils under evergreen trees were drier and earthworm biomass lower than soils under deciduous trees and lawns (see figs. 1 & 4 in study II), which can contribute to C and N accumulation under evergreen trees given the positive effects of soil moisture and earthworms on litter decomposition (Lavelle et al., 2004; Lee et al., 2014). Supporting this, results of the greenhouse gas emission study showed that soils under evergreen trees had consistently lower CO_2 and N_2O emissions than those under deciduous trees and lawns across the three sampling seasons (see fig. 4 in study I and fig. 3 in study II). Moreover, soil NH_4^+ content was lower under evergreen trees than under deciduous trees, which likely results from the slow N mineralisation (Knops et al., 2002; Lavelle et al., 2004) under evergreen trees due to the low quality of soil OM (see fig. S2D in study I) and low earthworm biomass there. Unexpectedly, NO_3^- content did not differ clearly among the three plant types, which may be due to the similar soil C/N ratios (see fig.1 in study II) among the plant types: soil C/N ratios have a strong effect on nitrification (Lovett et al., 2004; Gundersen et al., 2009). I acknowledge that results of the resin bags are the joint outcome of many soil N-related processes, given that soil N cycling is a very complex phenomenon containing many interlinking processes. Nevertheless, the results of this thesis suggest that, compared to deciduous trees and lawns, evergreen trees in urban parks have a higher ability to retain C and N in their soils by accumulating OM and reducing C and N outputs.

The high soil OM, C and N concentrations under evergreen trees also relate to high root production (I). Similar to boreal forests (Yuan and Chen, 2010), evergreen trees had higher root production compared to deciduous trees in both young and old parks (Fig. 5). Moreover, previous studies have shown that roots of conifer trees, similar to needle litter, associate with low decomposability and turnover rates (Silver and Miya, 2001; Yuan and Chen, 2010), which emphasises the potential contribution of root production to OM accumulation (Persson, 2012; Lin et al., 2020). However, the high root production under lawns in old parks did not transfer to high soil OM, C and N concentrations there, which may be explained by the labile and fast decomposing roots of grasses/herbs (Seastedt et al., 1992), and high earthworm biomass in lawns soils. Indeed, lawn soils always had the highest CO_2 emissions (C mineralisation) among the three plant types independent of sampling seasons and park age. These results suggest that root production – together with root quality (Silver and Miya, 2001) – plays an important role in OM accumulation also in urban greenspaces. Therefore, the first hypothesis that soil C and N accumulation relates to both litter decomposability and root production was supported. It is worth noting that, in this thesis, I studied plant type effects on soil C and N accumulation in the uppermost soil layer (0-10 cm) only. This is because previous studies have shown that the uppermost soil layer is often the most responsive layer to plant type (Jobbágy & Jackson, 2000, Setälä et al., 2016).

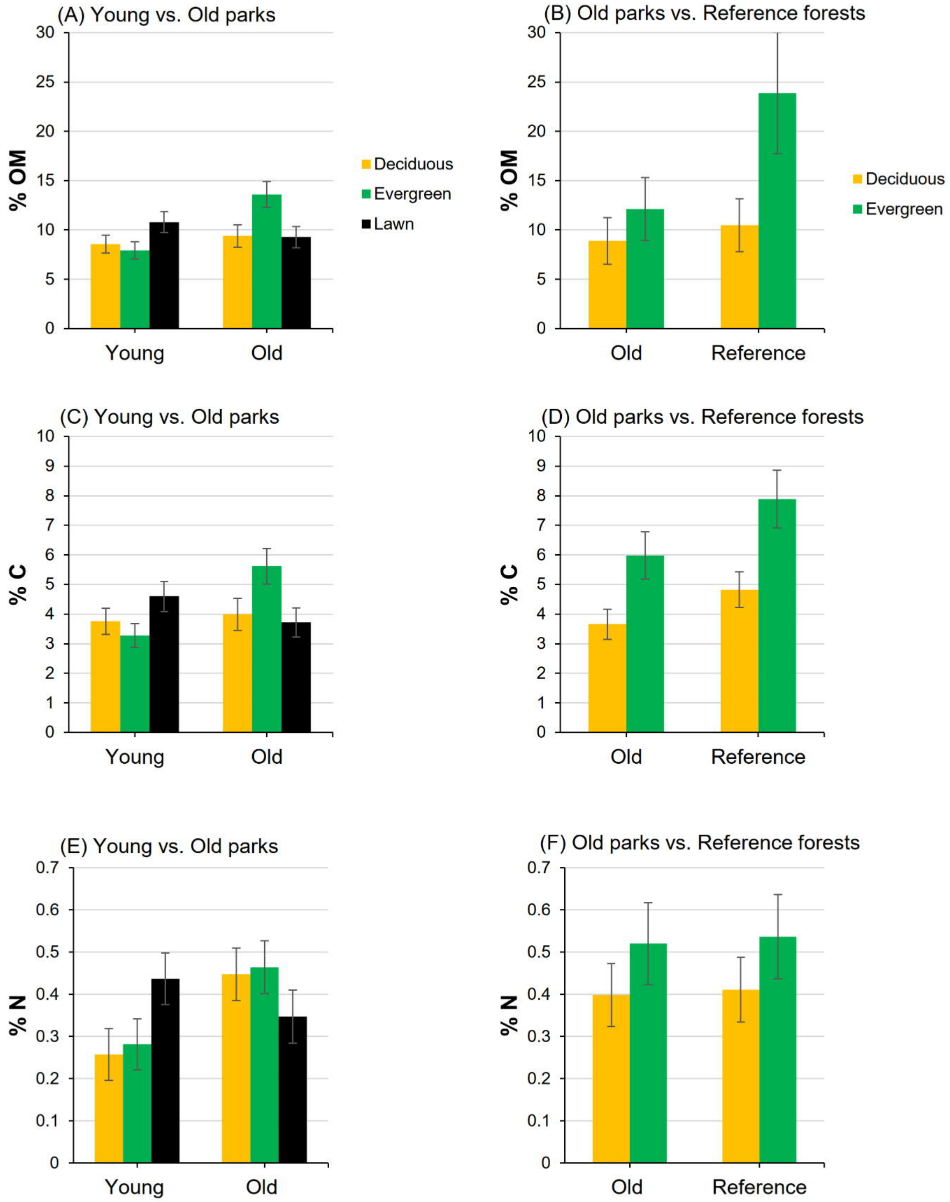

Figure 3. Differences in soil organic matter, carbon and nitrogen concentrations (predicted means ± SE) under different plant functional types (deciduous tree, evergreen tree, lawn) between young and

old parks (A, C, E), and between old parks and reference forests (B, D, F). Values for old parks in the two comparisons (young vs. old parks; old parks vs. reference forests) differ slightly due to predicted values.

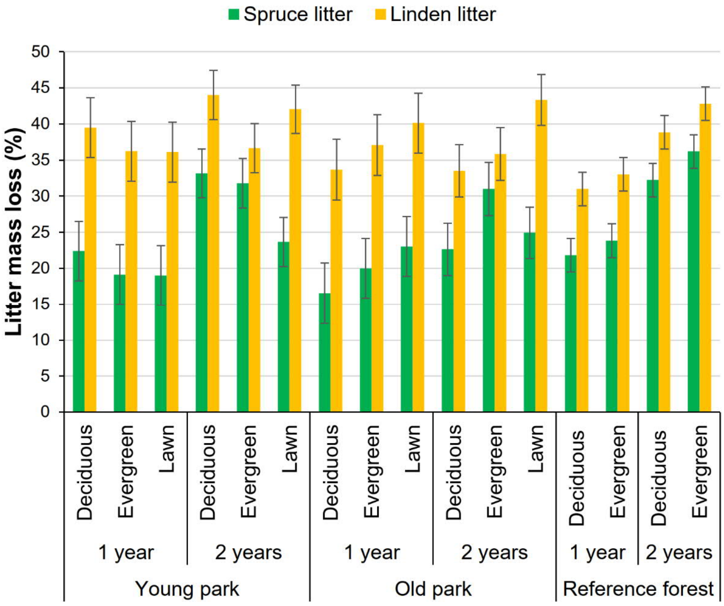

Figure 4. Differences in litter mass loss (% of the initial mass, predicted means ± SE) between spruce and linden litter under the three plant functional types (deciduous tree, evergreen tree, lawn) in young and old parks, and reference forests.

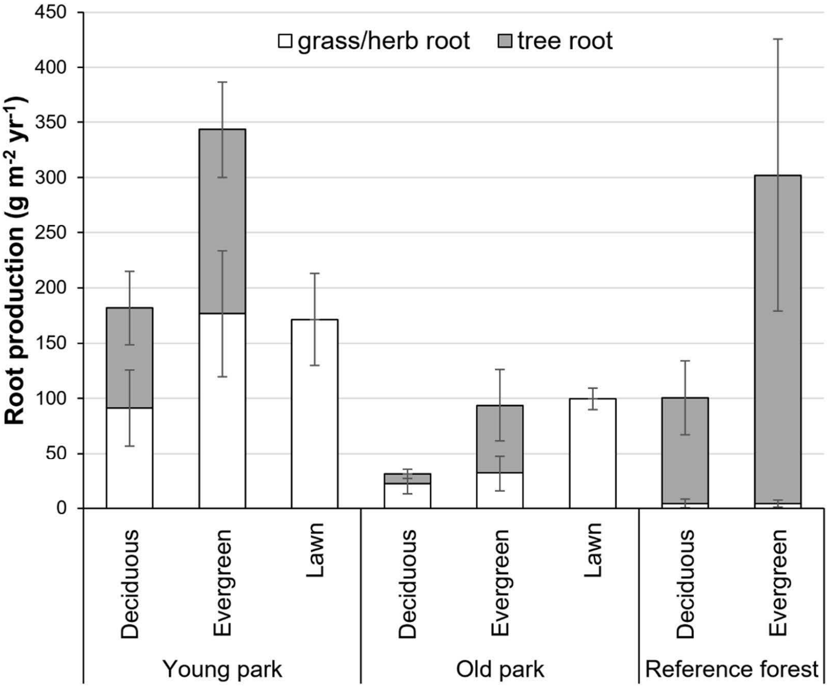

Figure 5. Root production (means ± SE) under the three plant functional types (deciduous tree, evergreen tree and lawn) in young and old parks, and reference forests. White bars refer to grass/herb roots, while grey bars refer to tree roots.

4.2 Effects of park age on the ability of plant functional type to influence soil C and N accumulation

Plant type effects on soil C and N accumulation were modulated by park age. Unlike in old parks, lawns had higher soil OM, C and N concentrations than those under the two tree types in young parks (Fig. 3), which is likely because it takes several decades for trees to manifest their effects on soil total OM, C and N in urban parks in boreal climates (see Setälä et al., 2016). Indeed, soil OM, C and N concentrations under evergreen trees significantly increased with park age. While, under deciduous trees, only soil N concentration increased with park age. Kaye et al. (2008) reported that litter removal from urban greenspaces substantially decrease C input into soils, but has only little effect on soil N concentration. Similarly, Kotze et al. (2021) reported that, despite litter removal, soil N in urban parks increased with park age in boreal and temperate climates. These results suggest that factors other than quantity of aboveground litter input affect soil N accumulation in urban parks. For example, the increased soil N concentration under the two tree types with park age may be due to the fact that old parks have been exposed to anthropogenic N deposition for a longer time than young parks. Unlike trees, the ability of lawn to retain N has been reported to decrease with age (Porter et al., 1980; Frank et al., 2006), which may explain the decreased soil N concentration under lawns with park age.

Surprisingly, although the effects of plant type on soil total C and N concentrations were clearly modulated by park age, the patterns of plant type effects on the input and output of C and N, e.g., litter decomposition, root production, greenhouse gas emissions and potential N leaching, were unresponsive to park age (I, II). This clearly suggests that the mechanisms through which plant type affects soil C and N dynamics are the same in young and old parks, which is likely due to the similar effects of plant type on soil physico-chemical properties and earthworm biomass in these two habitats (see figs. 1 & 4 in study II). Thus, the second hypothesis was supported. These findings suggest that, despite (i) the short period of time of plant-soil interactions, and (ii) recent construction disturbances in young parks, the ability of plant type to modify soil is strong enough in young parks to affect soil C and N dynamics (see also Setälä et al., 2016, 2017).

4.3 Comparisons of plant functional type effects on soil C and N dynamics between old urban parks and natural/semi-natural forests

By comparing these two habitats, I aimed at exploring the potential effect of management-induced disturbances on soils and their processes. Results show that plant type effects on soil C and N dynamics in old parks follow the same pattern as in reference forests (I, II). However, differences in soil total OM and C concentrations between evergreen and deciduous trees were greater in natural/semi-natural forests than in old parks (Fig. 3). This likely results from the much higher root production under evergreen trees than under deciduous trees in reference forests (Fig. 5), given that root-derived C can contribute to 70% of soil C storage in boreal forests (Clemmensen et al., 2013). Furthermore, soil mixing by earthworms (Edwards and Bohlen, 1996), abundantly present under deciduous trees in urban parks, may also overshadow the contribution of root production to OM accumulation in the uppermost soil layer (0-10 cm in this thesis). Interestingly, the difference in soil N concentration between the two tree types in old parks was almost the same as in natural/semi-natural forests (Fig. 3). This suggests that the excess N input in urban ecosystems do not weaken the plant type effect on soil N accumulation. Additionally, despite the efficient raking/removal of leaf litter in urban parks, soil OM and N concentrations under deciduous trees in old parks did not differ clearly from those in reference forests where leaves were not raked away. This result suggests that the effects of litter removal on soil OM and N concentrations are minimal under deciduous trees, and may also be compensated for by the production of grass/herb clippings that are left on site (Qian et al., 2003).

Surprisingly, despite the various disturbances and management practices in urban parks, the magnitude of plant type effects on litter mass loss, CO_2 and N_2O emissions, and inorganic N leaching was almost identical between the old parks and reference forests. This clearly suggests that the ability of plant type to control soil C and N dynamics in disturbed and N-saturated urban environments is as strong as in natural/semi-natural forests, which can be explained by the same magnitude of plant type effects on physico-chemical properties between old parks and reference forests (see also Kotze et al., 2021). For example, soils under evergreen trees always had the lowest pH and moisture content among the three plant types, independent of habitat (see fig. 1 in study II). Thus, the third hypothesis that plant type effects on soil C and N dynamics are less pronounced in urban parks than in natural/semi-natural forests was refuted. Collectively, similar to natural/semi-natural forests (Finzi et al., 1998; Hobbie, 2015), plant functional type can play a key role in controlling C and N dynamics in urban parks and thus merits to be acknowledged in, e.g. park management and planning.

4.4 Effects of soil sealing on soil C and N storage in urban areas

Soil sealing has substantial, negative impacts on soil C and N storage under boreal climate (III). In the top and middle layer (i.e. the construction layer), soil C and N concentrations underneath impervious surfaces were significantly lower than those underneath pervious surfaces (park lawns) (Fig. 6 A & B). This is not surprising given that OM-devoid materials, such as gravel, sand and rock, are used in the construction layer (Fig. 6C). Underneath impervious surfaces, C and N concentrations were similar between the first two layers. This, together with the fact that no roots were detected in the construction layer during samplings, indicates that sealed soils receive very little OM from aboveground through cracks and from belowground by root litter input after sealing. Interestingly, in the deepest soil layer (native soil layer), soil C and N concentrations underneath impervious surfaces did not differ much from those underneath pervious surfaces, which is in agreement with the results reported by Cambou et al. (2018). This suggests that native soil below the construction layer can retain C and N, which refers to slow OM degradation in sealed soils and the low soil microbial activity underneath impervious surfaces (see fig. 2H in study III, and Wei et al., 2013; Piotrowska-Długosz and Charzyński, 2015).

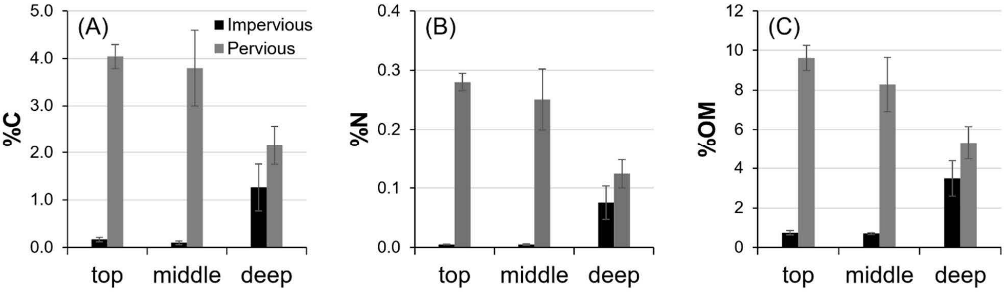

Figure 6. Concentrations (means ± SE) of soil carbon (A), nitrogen (B) and organic matter (C) under impervious and pervious surfaces at three depths (top layer: 0-10 cm under both impervious and pervious surfaces, middle layer: 45-55 cm under impervious surfaces; 11-20 cm under pervious surfaces, deep layer: 60-130 cm under impervious surfaces; 21-50 cm under pervious surfaces) in Lahti.

In the city of Lahti, soils (0-100 cm) underneath impervious surfaces can store 1.20 kg C m^{-2} and 0.04 kg N m^{-2}, respectively. In warmer countries with less intensive soil construction, the respective densities can be as high as 13.5 kg C m^{-2} (15-100 cm) in Leicester, UK (Edmondson et al., 2012), and 1.25 kg N m^{-2} (0-100 cm) in Yixing, China (Wei et al., 2014). These results show that C and N density of sealed soils in urban areas is 11 and 31 times, respectively, lower in boreal areas than in warmer countries, suggesting that the negative effect of soil sealing on soil C and N is much higher in boreal areas than in warmer areas. This is due to the need to remove massive top soil before sealing in boreal cities. For example, the depth of the construction layer is ca. 100 cm in Lahti but only 10-20 cm in cities located in warmer countries (Edmondson, et al., 2012; Wei et al., 2013). Based on the C and N density results in the Lahti city centre (see fig. 1 in study III), soils (0-100 cm) underneath impervious surfaces (265.1 ha) and pervious surfaces (146.3 ha) were estimated to store 3112 t and 46 538 t of C, and 105 t and 2750 t of N, respectively. Therefore, soils under impervious surfaces contribute only 6% of C and 4% of N to the C and N budgets in the city centre of Lahti. These results support the fourth hypothesis that soils underneath impervious surfaces play a smaller role in C and N accumulation compared to urban greenspace soils in boreal climate. Similarly, in his Master's work, Immonen (2020) estimated that, although impervious surfaces account for 89.6% of the total area in the city centre of Helsinki, only 25% of C and 12% of N were stored in soils underneath impervious surfaces to a depth of 50 cm, while 75% of C and 88 % of N were stored in soils in urban greenspaces that account for only 10.4% of the total area. This further emphasises the importance of urban greenspace soils in C and N storage in boreal climate (Setälä et al., 2016; Kotze et al., 2021).

5. CONCLUSIONS AND FUTURE PERSPECTIVES

In the context of rapid urbanisation and global climate change, knowledge on the capacity of urban greenspace soils to provide ecosystem services is needed to build more sustainable cities (Kumar and Hundal, 2016; Zhu et al., 2017). I explored, for the first time, the mechanisms by which plant type affects soil-derived ecosystem services, i.e. C and N accumulation, in urban greenspaces under boreal climate. Results of this thesis show that the ability of evergreen trees to accumulate C and retain N in soils relates to both the slow rate of litter decomposition and high root production. Moreover, evergreen trees modified soil properties by lowering soil pH and soil moisture content efficiently, both of which can retard litter decomposition and N denitrification. Furthermore, evergreen trees can have the potential to mitigate anthropogenic N pollution and climate change in urban environments by reducing greenhouse gas emissions as was shown in this thesis. More importantly, despite the various anthropogenic disturbances in urban parks, the mechanisms through which plant type controls soil C and N dynamics are independent of both habitat (urban parks vs. natural/semi-natural forests) and park age (young vs. old parks). These findings clearly suggest that plant type plays a key role in controlling soil-derived ecosystem services not only in natural environments but also in urban environments. Thus, this thesis provides applicable information to urban planners in terms of building more sustainable cities.

Results of this thesis also show that, in boreal cities, soils in urban greenspaces store substantially more C and N than soils under impervious surfaces. Moreover, soil sealing has much larger negative effects on soil C and N storage in boreal cities compared to cities in warmer countries, suggesting that previous, model-based estimates of C and N storage underneath impervious surfaces in warmer countries do not apply to cities under boreal climate. Thus, this thesis adds important, hitherto lacking information to be included in estimates on C and N storage of urban soils, both locally and globally. In boreal cities, the highly negative effect of soil sealing on C and N storage resulting from the massive top soil removal should be acknowledged in future urban planning. For example, reusing the OM-rich soils in urban areas rather than dumping them outside the city may reduce the release of C from soils to the atmosphere and prevent N leaching to surface and belowground waters.

This thesis highlights the importance of urban greenspace soils in ecosystem services provision under boreal climate. As the build-up of organo-mineral associations strongly affects soil OM stabilisation (Schmidt et al., 2011; Cotrufo et al., 2013), further research is needed to explore the potential effect of plant type on soil organo-mineral associations in urban greenspaces. For example, analyses of soil OM fractions and stable isotopes can be used to explore soil C and N pathways under divergent plant types (Bardgett et al., 2014; Su et al., 2021). Moreover, results of this thesis show that leaf litter removal has a very small impact on soils, which, in turn, emphasises the importance of roots in affecting soil-derived ecosystem services in urban areas. Further research is required to study how far away from trees plant-soil interaction extends in urban parks, which is important for determining optimal tree density in urban parks, and in accurately calculating C and N budgets at the park level.

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